NASA Technical Memorandum 103613

A Life Comparison of Tube and Channel Cooling Passages for Thrust Chambers

R.S. Jankovsky and J.M. Kazaroff
Lewis Research Center
Cleveland, Ohio

Prepared for the
1990 JANNAF Propulsion Meeting
Anaheim, California, October 3-5, 1990

NASA

A LIFE COMPARISON OF TUBE AND CHANNEL COOLING PASSAGES FOR THRUST CHAMBERS

R.S. Jankovsky and J.M. Kazaroff
National Aeronautics and Space Administration
Lewis Research Center
Cleveland, Ohio 44135

ABSTRACT

This report describes the life analysis used to compare copper tubes and milled copper channels for rocket engine cooling passages. Copper tubes were chosen as a possible replacement for the existing milled copper channel configuration because (1) they offer increased surface area for additional enthalpy extraction; (2) they have ideal pressure vessel characteristics; and (3) the shape of the tube is believed to allow free expansion, thus accommodating the strain resulting from thermal expansion. The analysis was a two-dimensional elastic-plastic comparison, using a finite element method, to illustrate that, under the same thermal and pressure loading, the compliant shape of the tube increases the life of the chamber. The analysis indicates that for a hot-gas-side-wall temperature of 1000 °F the critical strain decreases from 1.25 percent in the channel to 0.94 percent in the tube. Since the life of rocket thrust chambers is most often limited by cyclic strain or strain range, this decrease corresponds to an expected tube life which is nearly twice the channel life.

INTRODUCTION

The future cryogenic Space Transfer Vehicle Engine is required to have a long life and be reliable. This can be achieved with a thrust chamber that is compliant. Compliance can be inherent in tubular coolant passage construction, because this contour allows relatively free expansion. Free expansion accommodates and distributes the strains preventing local accumulation, and therefore extends the life of the chamber. This initial investigation is a simplified, relative comparison of the expected lives of milled cooling channels and tubular cooling passages. The analysis compares only plug-nozzle chambers that have been used at NASA Lewis Research Center for thrust chamber study and development (Fig. 1, Ref. 1). The plug-nozzle chamber has been tested and studied since the early 1970's and the milled channel configuration has been very well characterized. This investigation compares two plug-nozzle chamber configurations: (1) a milled OFHC copper channel type (Fig. 2); and (2) an OFHC copper tube bundle type (Fig. 3). The comparison is done at the same pressure loading (i.e., the same chamber pressure, and same coolant pressure) and the same thermal loading so that the pure compliance, or geometric benefit can be determined.

FIGURE 1. - PLUG-NOZZLE CHAMBER BEING TESTED AT NASA LEWIS RESEARCH CENTER.

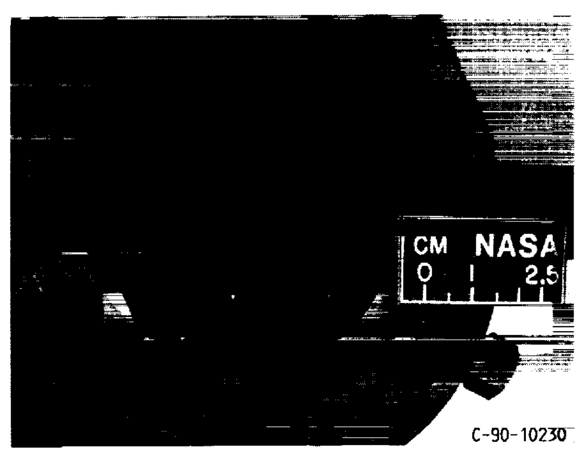


FIGURE 2. - CHANNEL PLUG-NOZZLE CHAMBER.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

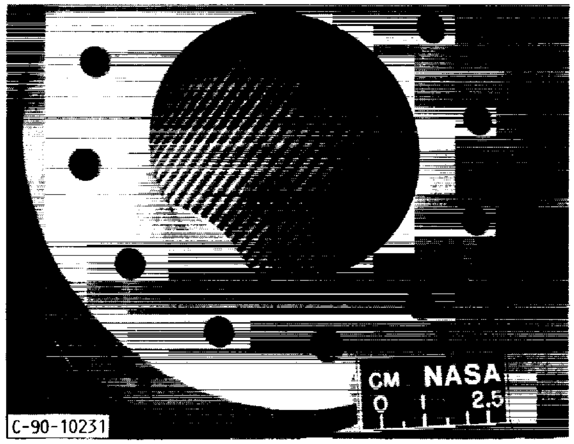


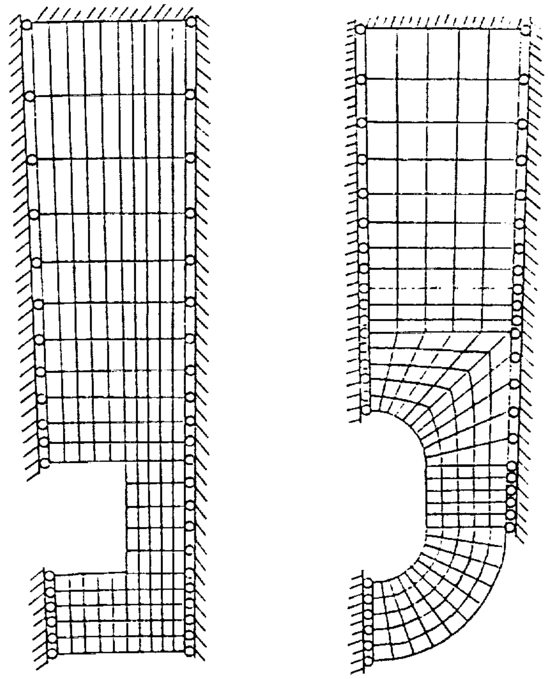
FIGURE 3. - TUBULAR PLUG-NOZZLE CHAMBER.

ANALYTICAL PROCEDURE

The analytical procedure consisted of a thermal analysis, a strain analysis, and a life correlation. This three part analysis was performed on a section through the throat of the thrust chamber. This area was selected for the analysis because the area of highest heat flux generally produces the highest thermal strains. The thermal analysis was performed using SINDA '85, a general purpose heat transfer/fluid program that simulates transient or steady-state energy storage and flow in a system modeled as a "thermal circuit." The steady state temperature profiles were determined for both the channel and tube structures. The channel model used 185 elements, and the tube model used 180 elements (Figs. 4(a) and (b)). The coolant temperature in both models was set at -360 °F to account for the warming of the hydrogen before it gets to the throat. The heat flux for the channel model was set at 33 Btu/in.^{2}/sec (Ref. 1). The maximum heat flux for the tube model was 33 Btu/in.^{2}/sec and decreased according to the profile reported in Ref. 2. This compensates for the thickening boundary layer about the periphery of the tube. The coolant-side film coefficient was varied in both models until a maximum hot-gas-side wall temperature of 1000 °F was obtained. (Ref. 1 shows that 1000 °F was the hot-gas-side wall temperature for past testing.)

The strain analysis was performed using a two-dimensional elastic-plastic MARC analysis. MARC is a general purpose finite element analysis program. Both strain models contained the same number of elements as their thermal models. The models consisted of 8-node, three-dimensional, isoparametric elements (MARC element 7). The strain analysis used the temperatures from the SINDA '85 analysis along with a chamber pressure of 600 psi and a coolant pressure of 1200 psi. (These are standard operating conditions for plug-nozzle tests.) (Ref. 1) The constraints were the same for both configurations. The cool outer structure was fixed and the nodes along the planes of symmetry assigned zero displacement perpendicular to these planes, but permitted to move in the radial direction (Figs. 4(a) and (b)). The material properties such as coefficient of thermal expansion (Fig. 5(a), Ref. 3), yield strength, and modulus of elasticity were input as a function of temperature (Figs. 5(b) and (c), Ref. 4). The strain analysis was done using two simplifying assumptions and is considered valid when making only relative comparisons. First, no creep analysis was performed. This absence of creep is considered a valid assumption for the analysis of the plug-nozzle chambers because of the short cycle duration (3.5 sec) (Ref. 1). Second, the first cycle was taken to be representative of all cycles to follow. The critical strains used for the life analysis were determined from taking into account the magnitude of the strains (from the finite element analysis) along with other effects such as "ratcheting" (from test experience) that are known to shorten life (Ref. 5). These critical strains at steady state conditions were used to determine life instead of the more complicated, transiently analyzed strain ranges used in other predictions.

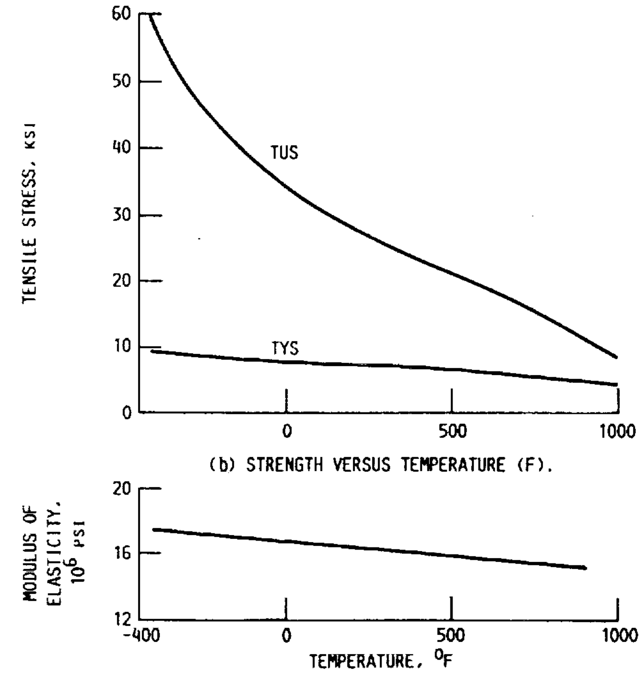
The life correlation was done using experimental low cycle fatigue data (Fig. 6, Ref. 6). This portion of the analysis was not meant to give an absolute value of life, rather it uses the low cycle fatigue data as a measure of the material's sensitivity to strain. Knowing the materials sensitivity to strain, and the relative decrease in strain, a life improvement prediction can be made (Refs. 7 and 8).



(a) 185 ELEMENT CHANNEL.

(b) 180 ELEMENT TUBE.

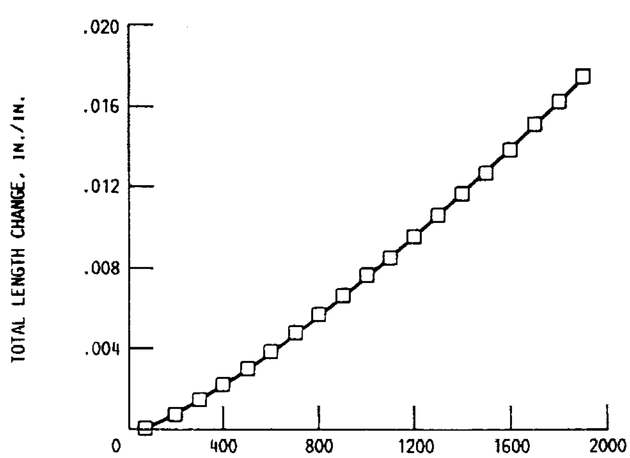
FIGURE 4. - MODELS WITH CONSTRAINTS.



(b) STRENGTH VERSUS TEMPERATURE (F).

(c) MODULUS OF ELASTICITY VERSUS TEMPERATURE.

FIGURE 5. - CONCLUDED.



(a) COEFFICIENT OF THERMAL EXPANSION VERSUS TEMPERATURE.

FIGURE 5. - OFHC COPPER MATERIAL PROPERTIES.

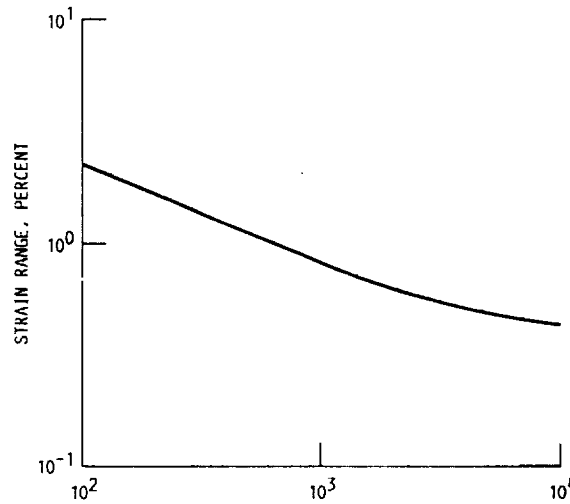


FIGURE 6. - TYPICAL LOW-CYCLE FATIGUE OF OFHC COPPER ANNEALED CONDITION AT $\dot{\epsilon} = 0.002\ \mathrm{sec}^{-1}$ IN ARGON AT 1000 $^{\circ}F$.

RESULTS

This analysis of the two chamber coolant passage configurations was undertaken to compare their cyclic lives. This effort began with the thermal analysis using SINDA '85. The SINDA '85 analysis resulted in steady state temperature profiles that are shown in Figs. 7 and 8. The maximum hot-gas-side wall temperature was set to 1000 °F and at this condition the profiles were very similar. The hottest elements were located at the center of the channel and at the crown of the tube.

With the thermal profiles, the material properties (as a function of temperature) and test pressures the strain analysis was performed. This resulted in the strain profiles of the two configurations as shown in Figs. 9 and 10. These strains are represented as Von Mises strains which are equivalent uniaxial strains. As can be seen from the strain contour (Fig. 9) for the channel structure, the location of the highest strain is at the center of the rib. This is not the typical failure site for this structure when chambers are actually tested, Fig. 11 shows an actual failure that has the rupture at the center of the cooling passage. This is not considered to be in error because in actual testing there are ratcheting affects (Ref. 9) taking place at the center of the channel which reduce the life dramatically (Ref. 5). The strain at the center of the channel is just slightly less than the maximum strain at the rib, but when combined with the racheting effect the critical strain area is at the center of the channel.

The strain contour (Fig. 10) for the tube structure shows that the highest strain occurs at the crown of the tube. The failure is expected to occur at the center line of the tube crown for the same reason as the channel above, high strain and racheting.

Figure 12 is a summary of the life analysis performed. The plot indicates experimental data of life as a function of hot-gas-side wall temperature for milled OFHC copper channel chambers (Ref. 1). It also shows the calculated life versus hot-gas-side wall temperature for the same configuration. There is very good agreement between the experimental data and the calculated data. The calculated data is slightly higher because of the simplifying assumptions made for the analysis and the fact that the number of cycles to failure was determined using low cycle fatigue specimen data. The low cycle fatigue specimen data is the average life at a particular strain range. The low cycle fatigue curve is based upon a series of data points which have a degree of scatter, consequently the line represents some average. Experimentally the plug-nozzle chambers are considered failed when the first sign of a crack through the wall occurs. These chambers have 72 channels, hence 72 fatigue specimens. Therefore, when the first crack occurs through the wall the weakest specimen is taken as the data point not the average as in the low cycle fatigue data. Figure 12 also shows the calculated life of the tube as a function of hot-gas-side wall temperature, showing that the tube cooling passage has promise of living approximately 100 percent longer than the channel cooling passage.

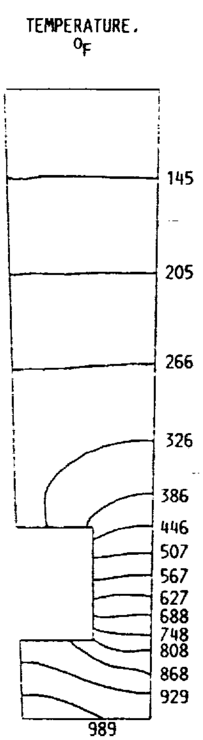


FIGURE 7. - CHANNEL MODEL TEMPERATURE CONTOURS.

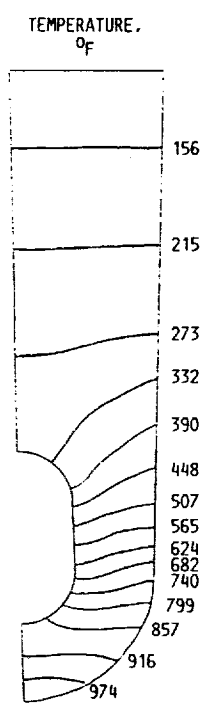


FIGURE 8. - TUBE MODEL TEMPERATURE CONTOURS.

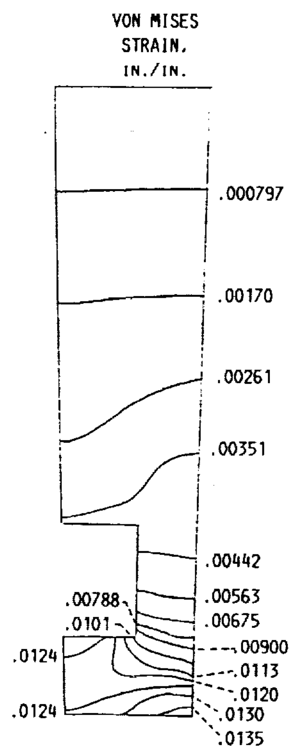


FIGURE 9. - CHANNEL MODEL STRAIN CONTOURS.

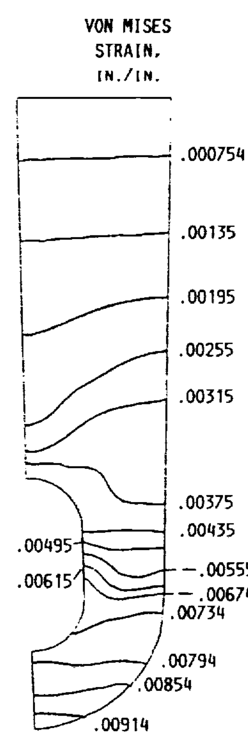


FIGURE 10. - TUBE MODEL STRAIN CONTOURS.

ORIGINAL PAGE
BLACK AND WHITE PHOTOGRAPH

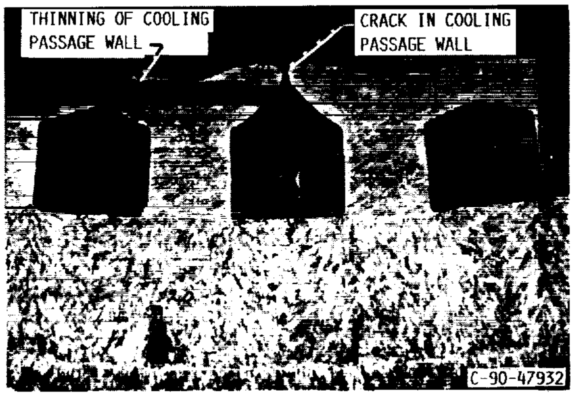


FIGURE 11. - TYPICAL CHANNEL WALL FAILURE.

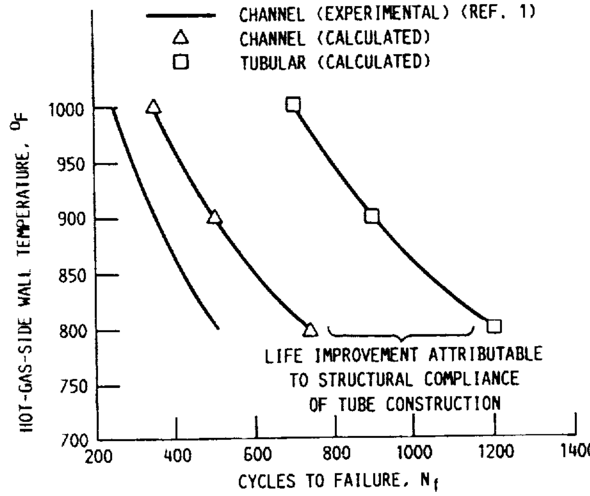


FIGURE 12. - HOT-GAS-SIDE WALL TEMPERATURE VERSUS CYCLES TO FAILURE.

SUMMARY OF RESULTS

An increase in life of a tubular coolant passage configuration, when compared to an equivalent channel configuration, of ~100 percent was found for hot-gas-side wall temperatures ranging from 800 to 1000 °F. A summary of critical strains along with the corresponding stresses and number of cycles to failure are provided in Fig. 13. A comparison of the number of cycles to failure as a function of hot-gas-side wall temperature for the channel and tube cooling passages is also provided in Fig. 13.

	HOT-GAS-SIDE WALL TEMPERATURE, °F	STRESS, PSI	CRITICAL STRAIN, IN./IN.	CYCLES TO FAILURE
MILLED CHANNEL PASSAGE	1000	8650	0.0125	350
	900	8025	0.0108	500
	800	8001	0.0091	740
TUBE PASSAGE	1000	6969	0.0094	700
	900	7081	0.0083	900
	800	7184	0.0073	1200

FIGURE 13. - SUMMARY TABLE OF HOT-GAS-SIDE WALL TEMPERATURE, STRESS, STRAIN, AND CYCLES TO FAILURE.

RECOMMENDATIONS

Three recommendations are made for tubular configuration life analysis. First, although this analysis is valid for relative comparisons of channel and tube structures, a three-dimensional visco-plastic analysis of the tube structure is required to get a accurate understanding of what is happening. Second, alloy tubes should be analyzed to determine if alloy properties are applicable when compliance is the goal. Third, the results of both this analysis and subsequent analyses need to be validated with testing.

REFERENCES

1. Quentmeyer, R.J.: Experimental Fatigue Life Investigation of Cylindrical Thrust Chambers. AIAA Paper 77-893, July 1977 (Also, NASA TM X-73665).

2. Kacynski, K.J.: A Three-Dimensional Turbulent Heat Transfer Analysis for Advanced Tubular Rocket Thrust Chambers. NASA TM-103293, 1990.

3. Schmidt, E.M.; Williams, L.R.; and Young, J.D.: Design and Development Engineering Handbook of Thermal Expansion Properties of Aerospace Materials at Cryogenic and Elevated Temperatures. (R-6981, Rockwell International; NASA Contract NAS8-19) NASA CR-102331, 1967.

4. Esposito, J.J.; and Zabora, R.F.: Thrust Chamber Life Prediction. Volume I: Mechanical and Physical Properties of High Performance Rocket Nozzle Materials. (D180-18673-1-Vol-1, Boeing Aerospace Co.; NASA Contract NAS3-17838), NASA CR-134806, 1975.

5. Manson, S.S.; and Halford, G.R.: Treatment of Multiaxial Creep-Fatigue by Strainrange Partitioning. 1976 ASME-MPC Symposium on Creep-Fatigue Interaction, R.M. Curran, ed., American Society of Mechanical Engineers, 1976, pp. 299-322.

6. Conway, J.B.; Stentz, R.H.; and Berling, J.T.: High Temperature, Low Cycle Fatigue of Copper-Base Alloys in Argon. Part 1: Preliminary Results for 12 Alloys at 1000 °F (538 °C). NASA CR-121259, 1973.

7. Shoji, J.M.: Advanced Hydrogen/Oxygen Thrust Chamber Design Analysis. (R-9258, Rockwell International; NASA Contract NAS3-16774), NASA CR-121213, 1973.

8. Andrus, J.S.; and Bourdeau, R.G.: Thrust Chamber Material Technology Program. P&W Report FR-20672, Pratt and Whitney, 1989.

9. Hannum, N.P.; Kasper, H.J.; and Pavli, A.J.: Experimental and Theoretical Investigation of Fatigue Life in Reusable Rocket Thrust Chambers. AIAA Paper 76-685, July 1976 (Also, NASA TM-X-73413).

NASA
National Aeronautics and Space Administration

Report Documentation Page

1. Report No. NASA TM-103613	2. Government Accession No.	3. Recipient's Catalog No.
4. Title and Subtitle A Life Comparison of Tube and Channel Cooling Passages for Thrust Chambers		5. Report Date
		6. Performing Organization Code
7. Author(s) R.S. Jankovsky and J.M. Kazaroff		8. Performing Organization Report No. E-5724
		10. Work Unit No. 591-41-21
9. Performing Organization Name and Address National Aeronautics and Space Administration Lewis Research Center Cleveland, Ohio 44135-3191		11. Contract or Grant No.
		13. Type of Report and Period Covered Technical Memorandum
12. Sponsoring Agency Name and Address National Aeronautics and Space Administration Washington, D.C. 20546-0001		14. Sponsoring Agency Code

15. Supplementary Notes

Prepared for the 1990 JANNAF Propulsion Meeting, Anaheim, California, October 3-5, 1990.

16. Abstract

This report describes the life analysis used to compare copper tubes and milled copper channels for rocket engine cooling passages. Copper tubes were chosen as a possible replacement for the existing milled copper channel configuration because (1) they offer increased surface area for additional enthalpy extraction; (2) they have ideal pressure vessel characteristics; and (3) the shape of the tube is believed to allow free expansion, thus accommodating the strain resulting from thermal expansion. The analysis was a two-dimensional elastic-plastic comparison, using a finite element method, to illustrate that, under the same thermal and pressure loading, the compliant shape of the tube increases the life of the chamber. The analysis indicates that for a hot-gas-side-wall temperature of 1000 °F the critical strain decreases from 1.25 percent in the channel to 0.94 percent in the tube. Since the life of rocket thrust chambers is most often limited by cyclic strain or strain range, this decrease corresponds to an expected tube life which is nearly twice the channel life.

17. Key Words (Suggested by Author(s)) Copper; Tube; Channel; Life; Rocket chamber	18. Distribution Statement Unclassified – Unlimited Subject Category 20

19. Security Classif. (of this report)	20. Security Classif. (of this page)	21. No. of pages	22. Price*
Unclassified	Unclassified	8	A02

NASA FORM 1626 OCT 86

*For sale by the National Technical Information Service, Springfield, Virginia 22161